

## Durham Research Online

---

### Deposited in DRO:

10 January 2016

### Version of attached file:

Other

### Peer-review status of attached file:

Peer-reviewed

### Citation for published item:

Lenz, Alexander (2013) 'What did we learn in theory from the Delta ACP Saga?', CHARM 2013 Manchester UK, 31 August - 4 September 2013.

### Further information on publisher's website:

<http://www.slac.stanford.edu/econf/C130831/>

### Publisher's copyright statement:

### Additional information:

---

### Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.



November 26, 2013

# What did we learn in theory from the $\Delta A_{CP}$ -saga?

ALEXANDER LENZ

*Institute for Particle Physics Phenomenology  
Durham University, DH1 3LE, Durham, UK*

The measurement of CP violation in the charm sector triggered a lot of theoretical activities and re-considerations. Nevertheless currently neither theory nor experiment have reached definite conclusions about the origin of a large CP violating effect in hadronic  $D$  decays. We review briefly (part of) the current theory literature and present as the most important outcome of the many investigations initial steps in a long journey to understand the standard model contribution to hadronic  $D$  meson decays from first principles as well as various control channels, that can be studied by experiment.

PRESENTED AT

The 6<sup>th</sup> International Workshop on Charm Physics  
(CHARM 2013)  
Manchester, UK, 31 August – 4 September, 2013

# 1 Introduction

The measurement of a non-vanishing CP-asymmetry in the charm sector by the LHCb Collaboration [1] end of 2011 - and also hints found by the CDF Collaboration [2] and the Belle Collaboration [3] - triggered an enormous amount of interest - about 200 citations at the time of writing this text - in the theory community, see e.g. [4–42]. Such a large amount of CP violation in the charm sector within the standard model was in contrast to common text book wisdom, see e.g. [43]\*.

Theorists unanimously identified NP to be the interpretation of this result, but the theoretical literature still does not give a homogeneous picture, whether NP abbreviates non-perturbative physics or new physics. Hence the two main organisers of CHARM 2013 have asked me to give an overview with the title *What did we learn in theory from the  $\Delta A_{CP}$ -saga?* - as a kind of independent point of view, since I did not publish on that topic†.

The proposed title‡ contains the two keywords  $\Delta A_{CP}$  and *saga*, on which I want to elaborate very briefly:

- $\Delta A_{CP}$  describes CP-violation in hadronic  $D$ -meson decays, see also [45–54]. It is defined as the difference of the CP asymmetries in the  $KK$  and  $\pi\pi$  final states.§

$$\Delta A_{CP} := A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-) . \quad (1)$$

The first measurements [1–3] gave a combined value of (see e.g. [57])

$$\Delta A_{CP} = -0.678 \pm 0.147\% . \quad (2)$$

This large value seemed to be in clear contrast to previous expectations within the standard model, e.g. [43]. Unfortunately the LHCb Collaboration performed further studies, where the significance went down [58] or which even resulted in a different sign [59]. Taking these new numbers into account the new combination turns out to be [60]

$$\Delta A_{CP} = -0.329 \pm 0.121\% . \quad (3)$$

The statistical significance for CP violation in hadronic  $D$  decays went now down considerably, but the central value is still larger than to be expected naively in the standard model. Here clearly further experimental input is needed to settle this issue.

---

\*Although there were also previously to the  $\Delta A_{CP}$  measurements claims that CP violation of the order of 1% cannot be completely excluded within the standard model, see e.g. [44] for the case of  $D$ -mixing.

†Scandalmonger claim it was because of a lack of valuable contributions to the Local Organisation Committee.

‡To my knowledge the first use of the phrase “ $\Delta A_{CP}$ -saga” was by Guy Wilkinson at BEAUTY 2013.

§See e.g. the reviews [55, 56] for some experimental background on the origin of this definition.

- According to Wikipedia *sagas* are described as "... tales of worthy men,...", describing their "battles and feuds". Battles and feuds clearly took place between proponents of large CP violating effects in  $D$  decays within the standard model and their opponents. Concerning the exclusion of women in the above quote, I would like to contradict Wikipedia and mention that more profound sources like [61] emphasise the crucial - albeit not always agreeable<sup>¶</sup> - role women played in sagas, e.g. *Hallgerd* from Njal's Saga or *Gudrun* in Laxdœla-Saga.

Starting the preparation of this talk, it was immediately clear that both the experimental and theoretical literature still do not give a very unique picture. Thus I started a poll among (worthy) colleagues to get some idea about the opinions inside the community and I posed the dictated title as the question:

*What did we learn from the  $\Delta A_{CP}$ -Saga?*

I received the following instructive answers:

- "...one should not jump on every  $3\sigma$ -effect..."
- "...it is very difficult for me to say what happens in  $D$ -decays..."
- "...we need a deeper understanding of QCD..."
- "... $\Delta A_{CP}$  in the standard model bigger than 0.1% is a stretch... ...original justification for considering enhanced penguins in  $D$  decays is somewhat weakened..."
- "...I don't really know what we can learn from  $\Delta A_{CP}$  at this moment..."
- "...since  $\Delta A_{CP}$  seems now significantly smaller, we believe that this is really a confirmation of our arguments for the standard model origin..."
- "...penguins are still very large and currently one cannot not decide if this can be of standard model origin without additional assumptions..."
- "... $\Delta A_{CP}$  should be at most a few times  $10^{-3}$  in the standard model..."
- "...making (reliable) theoretical predictions about  $\Delta A_{CP}$  is hard, but so is measuring it..."
- "...a value close to 1% is very unlikely in the standard model..."
- "...the most important thing I (re) learnt (over & over again) is that  $3\sigma$  experimental results are not really reliable! But LHCb did a great job in focusing on  $D$  decays"

---

<sup>¶</sup>Since I did not choose the title, I refuse to investigate this point thoroughly.

- “...preliminary data can change a lot... we have to probe 3- and 4-body final states...”

To proceed from this uniformly inconclusive effort, let us next look closer at the underlying structure of the  $D$ -meson decays.

## 2 Singly Cabibbo suppressed D-meson decays

$D$ -meson decays into two hadrons can be classified by their dependence on the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements:

1. CKM-favoured (CF) decays, like  $D^0 \rightarrow K^- \pi^+$ :  
This decay proceeds via the quark level decay  $c \rightarrow s \bar{u}$  and its CKM couplings are of order one. There are only tree-level contributions present.
2. Singly Cabibbo suppressed (SCS)  $D$ -meson decays, like  $D^0 \rightarrow \pi^- \pi^+$  or  $K^- K^+$ :  
This decay proceeds via the quark level decay  $c \rightarrow d \bar{u}$  (or  $c \rightarrow s \bar{s}$ ) and its CKM couplings are of the order of the Wolfenstein parameter  $\lambda$ . Now both tree-level contributions and penguins are present.
3. Doubly Cabibbo suppressed (DCS)  $D$ -meson decays, like  $D^0 \rightarrow \pi^- K^+$ :  
This decay proceeds via the quark level decay  $c \rightarrow d \bar{s}$  and its CKM couplings are of the order  $\lambda^2$  and there are only tree-level contributions present.

To get some CP violating contributions we need at least two different amplitudes and in the standard model this can only be fulfilled by the SCS decays where we have both tree level amplitudes and penguin amplitudes. Looking at the leading tree-level and penguin diagrams in the standard model one finds the following general structure of SCS decays

$$A(D^0 \rightarrow \pi^+ \pi^-) = V_{cd} V_{ud}^* (A_{Tree} + A_{Peng.}^d) + V_{cs} V_{us}^* A_{Peng.}^s + V_{cb} V_{ub}^* A_{Peng.}^b. \quad (4)$$

We have a tree-level amplitude  $A_{Tree}$  with the CKM structure  $V_{cd} V_{ud}^*$  and three penguin contributions  $A_{Peng.}^q$  with the internal quark  $q = d, s, b$  and the CKM structure  $V_{cq} V_{uq}^*$ . All additional, more complicated contributions like e.g. re-scattering effects can be put into the same scheme, see below. Already at that stage one can get a first feeling for the size of CP violating effects in the SCS  $D$  decays. Looking at the arising CKM elements one finds: 1)  $V_{cd} V_{ud}^* \approx -V_{cs} V_{us}^*$  and both are almost real and 2)  $V_{cb} V_{ub}^*$  is very small. Thus one expects very small CP violating effects in the standard model.

To become a little more quantitative we look in more detail into the structure of the

decay amplitude and we use the effective Hamiltonian for the description of the decay, which is essential for any numerical estimate. The amplitude is given by

$$A(D^0 \longrightarrow \pi^+ \pi^-) = \langle D^0 | \mathcal{H}_{eff} | \pi^+ \pi^- \rangle, \quad (5)$$

with the effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[ \lambda_d (C_1 Q_1^d + C_2 Q_2^d) + \lambda_s (C_1 Q_1^s + C_2 Q_2^s) + \lambda_b \sum_{i>3} C_i Q_i \right]. \quad (6)$$

The CKM structures are denoted by  $\lambda_x := V_{cx}^* V_{ux}$ .  $Q_{1,2}^q$  are tree-level operators for the decays  $c \rightarrow s + u\bar{s}$  (for  $q = s$ ) and  $c \rightarrow d + u\bar{d}$  (for  $q = d$ ),  $Q_{3\dots}$  are the penguin operators triggering the decays  $c \rightarrow u + d\bar{d}$  and  $c \rightarrow u + s\bar{s}$ . To obtain the amplitude one has to insert these operators in all possible ways into Feynman diagrams of the effective theory with a  $D^0$  as initial state and a pion pair in the final state. One gets

$$A = \frac{G_F}{\sqrt{2}} \left[ \lambda_d \sum_{i=1,2} C_i \langle Q_i^d \rangle^{T+P+E+R} + \lambda_s \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} + \lambda_b \sum_{i>3} C_i \langle Q_i^b \rangle^T \right]. \quad (7)$$

Here we use the following notation:

- $\langle Q \rangle^T$ : tree-level insertion of the operator  $Q$ ,
- $\langle Q \rangle^E$ : insertion of the operator  $Q$  in a weak exchange diagram,
- $\langle Q \rangle^P$ : insertion of the operator  $Q$  in a penguin diagram,
- $\langle Q \rangle^R$ : insertion of the operator  $Q$  in a re-scattering diagram.

As promised, Eq.(7) still has the same principal structure as Eq.(4). To proceed further we have a closer look into the arising CKM elements. Expressing them in terms of three mixing angles ( $\theta_{12}, \theta_{23}, \theta_{13}$ ) and one complex phase ( $\delta_{13}$ ) one gets in the standard parameterisation of the quark mixing matrix

$$\begin{aligned} \lambda_d &= -s_{12}c_{12}c_{23}c_{13} - c_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}}, \\ \lambda_s &= +s_{12}c_{12}c_{23}c_{13} - s_{12}^2 s_{23}s_{13}c_{13}e^{i\delta_{13}}, \\ \lambda_b &= +s_{23}s_{13}c_{13}e^{i\delta_{13}}, \end{aligned} \quad (8)$$

with the abbreviations  $c_{ij} := \cos(\theta_{ij})$  and  $s_{ij} := \sin(\theta_{ij})$ . Keeping in mind the following hierarchies:  $c_{ij} \propto \mathcal{O}(1)$ ,  $s_{12} \propto \mathcal{O}(\lambda)$ ,  $s_{23} \propto \mathcal{O}(\lambda^2)$ ,  $s_{13} \propto \mathcal{O}(\lambda^3)$ , one nicely sees that all potential CP violating effects are at least  $\mathcal{O}(\lambda^5)$  and thus heavily suppressed in the standard model. Using the unitarity of the CKM matrix -  $\lambda_s = -\lambda_d - \lambda_b$  - we get for the amplitude

$$A = \frac{G_F}{\sqrt{2}} \lambda_d \left[ \sum_{i=1,2} C_i \langle Q_i^d \rangle^{T+P+E+R} - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} + \frac{\lambda_b}{\lambda_d} \left( \sum_{i>3} C_i \langle Q_i^b \rangle^T - \sum_{i=1,2} C_i \langle Q_i^s \rangle^{P+R} \right) \right], \quad (9)$$

which can be abbreviated as

$$A =: \frac{G_F}{\sqrt{2}} \lambda_d T \left[ 1 + \frac{\lambda_b P}{\lambda_d T} \right]. \quad (10)$$

The definitions of  $T$  and  $P$  can be simply read off from the comparison of Eq.(9) with Eq.(10). Physical observables like branching ratios or CP asymmetries can be expressed in terms of  $|T|$ ,  $|P/T|$  and the strong phase  $\phi = \arg(P/T)$  as

$$Br \propto \frac{G_F^2}{2} |\lambda_d|^2 |T|^2, \quad (11)$$

$$a_{CP} = 2 \left| \frac{\lambda_b}{\lambda_d} \right| \sin \delta_{13} \left| \frac{P}{T} \right| \sin \phi = 0.0012 \left| \frac{P}{T} \right| \sin \phi. \quad (12)$$

In the last line we have used numerical input from [62] (see [63] for similar results) for the CKM elements. Up to this point all expressions are reliable and to an excellent accuracy exact and we are left with the subtlety that the values of  $|P/T|$  and the strong phase  $\phi$  are unknown.

### 3 Welcome to the Sagaland

The theoretical challenge in calculating the standard model value of  $\Delta A_{CP}$  is now boiled down to the determination of matrix elements of the form  $\langle D^0 | Q | \pi^+ \pi^- \rangle$ . Unfortunately we do not know if the tools that are very successful in  $B$ -decays or kaon decays can be applied to the charm system, whose mass scale is somehow intermediate, not really heavy, but also not light.

In order to proceed, additional assumptions have to be made, which might turn out in future to be unjustified. Since time by time real battles and feuds were fought over these assumptions I decided to term them ideologies. Roughly speaking one finds the following classes of assumptions:

- Ideology I: NP = non-perturbative physics
- Ideology II: NP = New Physics
- Ideology III: Symmetry rules
- Ideology IV: Experimentalists have to work harder

Unfortunately I will not be able to disproof any of these ideologies, which are discussed in more detail below.

### 3.1 This is clearly the standard model

It is well known that non-perturbative effects can sometimes be huge, see e.g. the very famous  $\Delta I = 1/2$  rule in  $K \rightarrow \pi\pi$  decays. Thus something similar might be acting in  $\Delta A_{CP}$ . A good starting point for defending this ideology might be the assumption of a order one strong phase. This gives

$$\left. \begin{aligned} \sin \phi &= 1 \\ \Delta A_{CP} &= -0.329\% \end{aligned} \right\} \Rightarrow \left| \frac{P}{T} \right| = 1.3 . \quad (13)$$

The current central experimental value for CP violation in hadronic  $D$  decays could be reproduced if  $|P/T|$  is enhanced roughly by one order of magnitude compared to naive standard model estimates, being discussed in the next subsection. Such an enhancement might be compared to the famous  $\Delta I = 1/2$  rule, which describes the ratio of the isospin zero part of the  $K \rightarrow \pi\pi$  amplitude compared to the isospin two part:

$$\frac{\Re(A_0)}{\Re(A_2)} := \frac{\Re[A(K \rightarrow \pi\pi)_{I=0}]}{\Re[A(K \rightarrow \pi\pi)_{I=2}]} = 22.5 . \quad (14)$$

This large experimental value contradicted naive estimates which expected a ratio close to one. The inclusion of renormalisation group running effects enhanced the value to about two [64, 65] which was still far off the measured number.

$$\frac{\Re(A_0)}{\Re(A_2)} = \begin{cases} 1 & \text{Naive} \\ 2 & \text{pert. QCD} \end{cases} . \quad (15)$$

One possible explanation for the large measured value might be a huge non-perturbative enhancement of penguin contributions to the decay  $K^0 \rightarrow \pi^+\pi^-$ . Such penguins would however only contribute to the  $I = 0$  final state. If this would be the case, then it might seem kind of obvious to expect a similar, maybe less pronounced effect in  $D^0$  decays, that could then explain the large experimental value of  $\Delta A_{CP}$ . This potential analogy was mentioned several times in the theory literature appearing after [1], see e.g. [10, 21, 40] or [20, 37, 39]; earlier references are e.g. [66] or [67]. It is quite interesting to note at this stage that we recently gained quite some considerable improvement in the theoretical understanding of the  $\Delta I = 1/2$  rule. Lattice calculations [68] (based on earlier ideas of Lüscher [69–71] and Lellouch, Lüscher [72]) give a value that is now much closer to experiment

$$\frac{\Re(A_0)}{\Re(A_2)} = 12.0 . \quad (16)$$

Moreover the large value of [68] arises from a strong suppression of  $A_2$  by “surprising” cancellations, which strongly depend on the values of quark masses, while no sizable penguin enhancement of  $A_0$  is found. At first sight this might seem to discourage the



idea that a large non-perturbative enhancement is responsible for the measured value of  $\Delta A_{CP}$ . But one has to keep in mind, that it is currently not clear, how to relate the lattice results for the  $K$ -decays to  $D$ -decays. Compared to the kaon case we have in  $D$ -decays different values of the quark masses (remember the strong dependence of the lattice result on that) and in a  $D$ -meson decay many more intermediate states are possible. First steps for a determination of hadronic two-body  $D$ -decays on the lattice have been presented in [73]. So here we will have to wait for future theoretical improvements, but the current status looks quite promising.

Assuming  $\sin \phi = 1$  the authors of [6] got values like  $\Delta A_{CP} = 0.3\%$  as “plausible” standard model predictions. They pointed out that a large value of  $|P/T|$  requires the matrix elements of the  $Q^s$  operators to be of similar size than the ones of the  $Q^d$  operators - this requirement can be read off from Eq.(9). For such an enhancement of contracted contributions over uncontracted ones (and a corresponding breakdown of the  $1/m_c$  expansion) the authors of [6] were also able to find - under certain assumptions - both experimental as well as theoretical evidence.

### 3.2 This is clearly new physics

It is well known that the heavy quark expansion (HQE) works very well in the  $b$ -system. Recently it was even found that also quantities where this expansion might be questionable because of a small energy release in the decay, are very well described by the theory, see e.g. the discussion in [74]. The prime example is the decay rate difference  $\Delta\Gamma_s$  of neutral  $B_s$  mesons. This observable is governed by the quark level decay  $b \rightarrow c\bar{c}s$ , with a limited phase space in the final state because of the two massive charm quarks. Recent measurements [75–78] agree impressively well with the standard model prediction [79] based on the calculations in [80–84].

$$\left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\text{Exp}} \bigg/ \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^{\text{SM}} = 0.92 \pm 0.12 \pm 0.20 , \quad (17)$$

where the first error is the experimental uncertainty and the second one the conservatively estimated theory error. The experimental average has been taken from [60]. If the HQE works so well in the  $b$ -system it seems reasonable to assume that this expansion delivers some rough but reliable estimates in the  $c$ -system. The analogue of  $\Delta\Gamma_s$  in the neutral  $D$ -system is the mixing quantity  $y$ . Unfortunately there is an almost perfect GIM cancellation in the leading HQE term of  $y$  and thus this quantity is either governed by higher order terms in the HQE or by non-perturbative contribution, see e.g. [44]. Thus a better testing ground for inclusive  $c$ -decays seems to be the ratio of  $D$ -meson lifetimes, where no such cancellation occurs. Therefore one can test with these observables if the experimental number agrees with the first few terms in the HQE. Recent theoretical results [85] seem to indicate that the HQE is capable

of explaining the large observed ratios,

$$\frac{\tau(D^+)^{\text{Exp}}}{\tau D^0} = 2.536 \pm 0.019 , \quad (18)$$

$$\frac{\tau(D^+)^{\text{HQE}}}{\tau D^0} = 2.2 \pm 1.7(0.4) . \quad (19)$$

Currently the theory prediction is limited by the fact that there exists no lattice calculation for the arising matrix elements of four quark operators. Such a calculation is clearly doable with current technology. Using vacuum insertion approximation and assuming large uncertainties for the arising bag parameters one gets a theory uncertainty of  $\pm 1.7$ . Using similar errors as in the lattice results<sup>||</sup> for  $B$ -meson lifetimes one gets a theory uncertainty of  $\pm 0.4$ . Hence doing the corresponding lattice calculation seems clearly to be a worthy exercise.

Despite these being some interesting observations one has to keep in mind, that it is a priori not clear what inclusive arguments tell us about exclusive  $D$ -decays. Nevertheless we might gain or loose some confidence in applying methods relying on a  $1/m_c$  expansion, as we are doing now.

“Naive” perturbative estimates that seem to be valid in the  $B$ -system give, see e.g. [5], a very small expectation for  $|P/T|$

$$\left| \frac{P}{T} \right| \approx \frac{\alpha_s}{\pi} \approx \frac{0.35}{\pi} \approx 0.11 , \quad (20)$$

which is of a similar size as values obtained within the framework of QCD factorisation for  $D$ -decays see e.g. [6, 47, 48, 54]

$$\left| \frac{P}{T} \right| \approx 0.08 \dots 0.23 . \quad (21)$$

In contrast to the previous subsection we consider now  $\sin \phi \approx 0.1^{**}$  as a good starting point to obtain the standard model expectation for  $\Delta A_{CP}$

$$\Rightarrow a_{CP}^{\text{SM}} \approx (1.0 \dots 2.8) \cdot 10^{-5} , \quad (22)$$

which is about two orders of magnitude lower than the measured number - thus clearly new physics is at work.

Now one could start to investigate whether the observed value of  $\Delta A_{CP}$  can be solely due to new physics. This could be done model-independently, see e.g. [5, 17, 23, 26, 29] or by studying explicit models for physics beyond the standard model. To get some ideas about the covered models I give a brief but incomplete list of models and

---

<sup>||</sup>Unfortunately the most recent results [86] for  $B$ -meson lifetimes are from 2001!

<sup>\*\*</sup>I did not find any strong exclusion argument of this assumption, aimed to hyperbolise.

references: a model with an extra chiral fermion generation [8, 16, 31]<sup>††</sup>, models with an extended scalar sector [9, 14], SUSY [13, 17, 22], models with an extended gauge sector [7, 14], weakly couple new physics [24], composite Higgs models [27, 35], models with a L-R symmetry [28, 30], models with extra dimensions [32, 35], models with extra vector quarks [34] and models with scalar diquarks [15].

### 3.3 What did we learn from $SU(3)_F$ ?

As long as we have no method to calculate the  $D \rightarrow hh$  decays reliably from first principles, one of the best strategies is probably the investigation of symmetries, in particular flavour symmetries like  $SU(3)_F$  and  $U$ -spin. At first sight this approach seems to be discouraged by measurements like

$$Br(D^0 \rightarrow K^+ K^-) = 2.8 Br(D^0 \rightarrow \pi^+ \pi^-) , \quad (23)$$

which are in sharp contradiction to the expectation of equal branching ratios in a  $SU(3)_F$ -symmetric world. A recent fit [42]<sup>‡‡</sup> of the available  $D \rightarrow PP$  decay data (16 branching ratios, 10 CP asymmetries and one strong phase) including linear  $SU(3)_F$  breaking terms in the theoretical expressions finds that nominal  $SU(3)_F$  breaking, i.e. about 30% on the amplitude level can explain all data, also the one in Eq.(23). This conclusion can be found several times in the literature, nevertheless some comments are in order here:

- The fits in [42] allow of course also large, i.e. non-nominal  $SU(3)_F$  breaking.
- Some authors e.g. [20, 92] come to different conclusions - i.e.  $SU(3)_F$  breaking has to be large.
- If the  $SU(3)_F$  breaking is nominal in the fits of [42], then the data requires a very strong penguin enhancement. This is driven not only by  $\Delta A_{CP}$  but also by CP asymmetries in  $D^0 \rightarrow K_S K_S$ ,  $D_s \rightarrow K_S \pi^+$  and  $D_s \rightarrow K^+ \pi^0$ .

To draw some definite conclusions about the actual size of the  $SU(3)_F$  breaking and the penguin enhancement more precise data are necessary.

### 3.4 Experimental cross checks

Even if “experimentalists have to work harder” sounds a like theorists joke, following this path will probably be the most successful short-term way in understanding the

---

<sup>††</sup>Adding simply a fourth, perturbative, chiral family of fermions could recently be excluded [87–89] using electro-weak precision data and Higgs-searches.

<sup>‡‡</sup>This is an update of [39],  $SU(3)_F$  was also previously investigated e.g. in [10, 12, 16, 17, 19–21, 23, 25, 38, 40, 90, 91].

origin of  $\Delta A_{CP}$ . In my opinion the most profound result of the numerous theory investigations [4–42] was the identification of many decay channels for testing different theoretical assumptions. I will give some examples below - to get an exhaustive overview the reader will have to study the above quoted literature:

- In the standard model one has only  $\Delta I = 1/2$  penguins, thus any CP violation in a  $\Delta I = 3/2$  final state can only be due to new physics. An example for such a decay is, see e.g. [6, 23, 37, 39, 42]

$$D^+ \rightarrow \pi^+ \pi^0 . \quad (24)$$

- The assumption that  $SU(3)_F$  symmetry including nominal breaking holds, can be tested by investigating decays like  $D^0 \rightarrow K_S K_S$  (e.g. [21, 37, 39, 42]),  $D_s \rightarrow K_S \pi^+$  (e.g. [39, 42]) and  $D_s \rightarrow K^+ \pi^0$  (e.g. [39, 42]). These are the decays that drive the penguin enhancement in the  $SU(3)_F$  fits. Similar tests can be performed by comparing  $D^0 \rightarrow K^+ K^-$  with  $D^0 \rightarrow \pi^+ \pi^-$  or  $D^+ \rightarrow \bar{K}^0 K^+$  with  $D_s \rightarrow K^+ \pi^0$  (e.g. [39, 42]). In [23, 38] several sum rules have been set up, that can also be used to test the applicability of the  $SU(3)_F$  symmetry.
- Decays like  $D^+ \rightarrow \phi \pi^+$  and  $D_s \rightarrow \phi K^+$  are triggered by the same effective Hamiltonian as  $\Delta A_{CP}$ , so one might expect there also some sizable CP violating effects [16], if CP violation in hadronic  $D$ -decays is real.
- A good new physics candidate for a penguin enhancement is the chromomagnetic operator, see e.g. [5, 13, 24, 26, 32, 36] This possibility is, however, constrained by D-mixing and direct CP violation in the kaon system,  $\epsilon'/\epsilon$ . Moreover it might lead to observable effects in e.g.  $D \rightarrow P^+ P^- \gamma$ ,  $D \rightarrow \rho^0 \gamma$ ,  $D \rightarrow \omega \gamma$  and the corresponding CP asymmetries of these decays. Such a possibility could also lead to enhanced electric dipole moments of the neutron, see e.g. [24].
- An investigation of multi-body  $D$ -decays was suggested e.g. in [4, 23]. First experimental results are discussed in [93–95].
- It is also instructive, see e.g. [41] to measure the amount of indirect CP violation in the decays  $D \rightarrow \pi^+ \pi^-$  and  $D \rightarrow K^+ K^-$ , denoted by  $A_\Gamma(\pi\pi)$  and  $A_\Gamma(KK)$ . First results were just recently announced at this conference and published in [97].

## 4 Conclusion

The LHCb results for CP violation in hadronic  $D$ -meson decays triggered a lot of interest. Unfortunately both the experimental situation as well as the theoretical

interpretation are still not settled. So, “what did we really learn in theory from the  $\Delta A_{CP}$ -saga?”

The first result, although quite mundane and trivial: charm physics is interesting. Of course, there was quite a number of researchers who found this out before, but it seems that now charm physics came back on stage and it is now more generally considered to be a hot topic, which leads to an increased number of theoretical and experimental activities.

Next, some more profound achievements: even if we are still far away from a complete theoretical understanding of the hadronic structure of the  $D \rightarrow hh$  decays within the standard model, several important insights have been gained:

- Values for  $\Delta A_{CP}$  of several per mille require a very sizable enhancement of penguin contributions. Some authors find such values within the standard model plausible, while one might also argue for standard model values of  $\Delta A_{CP}$  of the order of  $10^{-5}$ .
- New lattice results for kaon decays do not find a huge non-perturbative enhancement of penguin contributions in  $K \rightarrow \pi\pi$  decays.
- It is a priori not clear how to extrapolate the lattice results for the kaons to the charm sector. But first investigations of hadronic  $D$ -meson decays on the lattice seem to indicate that such an endeavour might be doable, even if this will be a long term project.
- Recently we also learnt that the expansions in the inverse of the heavy quark mass work also very well for “critical” inclusive observables in the  $b$ -quark system. Thus it might seem not completely hopeless to apply such an expansion in the charm system. The ideal testing ground for this would be the ratios of  $D$ -meson lifetimes. To make some decisive statements, the lattice results for the arising matrix elements of four-quark operators - the “only” missing part - have to be determined. A task which clearly can be done with present techniques. This test will be very instructive, but even if it turns out that  $D$ -meson lifetime ratios can be described within the heavy quark expansion, it is still not completely clear what this means for exclusive decays. Nevertheless it might strengthen or weaken our confidence in applying methods like QCD factorisation to  $D \rightarrow hh$  decays.

The third class of insights were gained from  $SU(3)_F$  symmetry investigations. As long as we cannot treat the problem from first principles, symmetries are probably the best tools to approximate the problem. Currently there are many indications that nominal  $SU(3)_F$  breaking combined with a large enhancement of penguins could describe all  $D \rightarrow PP$  data. To draw definite conclusions, however, more data are necessary.

Finally the most concrete outcome of the theoretical investigations so far was the identification of numerous experimental channels, that allow a definite test of different theoretical assumptions.

Despite there were several interesting theory results obtained by investigations of new physics effects in  $\Delta A_{CP}$  I did not concentrate on individual models, because I consider the question whether the results in Eq.(2) or Eq.(3) can be of standard model origin as pivotal.

All in all, quite a lot has been already learnt in theory from the  $\Delta A_{CP}$ -saga and it seems the story will go on, both in theory and experiment. Shedding more light on the possible size of penguin contributions will also be crucial in  $B$ -physics, e.g. the penguin pollution in  $B_s \rightarrow J/\psi\phi$ .

A final comment: since the current literature is still (necessarily) full of prejudices it might also be interesting to know the prejudice of the author of this proceedings: the old central value in Eq.(2) is a clear signal for new physics and even if it is a kind of hair-splitting: going back to the original meaning of plausible (stemming from *lat. plausibilis*, which again originates from *plaudere*), I think that a standard model origin of a large value for  $\Delta A_{CP}$  is not plausible, but currently it can also not be excluded completely.

## ACKNOWLEDGEMENTS

I am grateful to I. Bigi, J. Brod, T. Feldmann, G. Hiller, G. Isidori, A. Kagan, J. Kamenik, H. Li, U. Nierste, L. Silvestrini, A. Soni and J. Zupan for taking part in the poll. I also benefited a lot from discussions with M. Jung, J. Kamenik, A. Kronfeld, S. Schacht and L. Silvestrini. Finally many thanks to Marion Lenz, Mathilde Lenz, Rainer Schenk and Ursula Schenk for providing me the time for writing up these proceedings in a period, where I should have spent my time differently.

## References

- [1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **108** (2012) 111602 [arXiv:1112.0938 [hep-ex]].
- [2] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **109** (2012) 111801 [arXiv:1207.2158 [hep-ex]].
- [3] B. R. Ko [Belle Collaboration], arXiv:1212.1975.
- [4] I. I. Bigi and A. Paul, JHEP **1203** (2012) 021 [arXiv:1110.2862 [hep-ph]].

- [5] G. Isidori, J. F. Kamenik, Z. Ligeti and G. Perez, Phys. Lett. B **711** (2012) 46 [arXiv:1111.4987 [hep-ph]].
- [6] J. Brod, A. L. Kagan and J. Zupan, Phys. Rev. D **86** (2012) 014023 [arXiv:1111.5000 [hep-ph]].
- [7] K. Wang and G. Zhu, Phys. Lett. B **709** (2012) 362 [arXiv:1111.5196 [hep-ph]].
- [8] A. N. Rozanov and M. I. Vysotsky, arXiv:1111.6949 [hep-ph].
- [9] Y. Hochberg and Y. Nir, Phys. Rev. Lett. **108** (2012) 261601 [arXiv:1112.5268 [hep-ph]].
- [10] D. Pirtskhalava and P. Uttayarat, Phys. Lett. B **712** (2012) 81 [arXiv:1112.5451 [hep-ph]].
- [11] H. -Y. Cheng and C. -W. Chiang, Phys. Rev. D **85** (2012) 034036 [Erratum-ibid. D **85** (2012) 079903] [arXiv:1201.0785 [hep-ph]].
- [12] B. Bhattacharya, M. Gronau and J. L. Rosner, Phys. Rev. D **85** (2012) 054014 [arXiv:1201.2351 [hep-ph]].
- [13] G. F. Giudice, G. Isidori and P. Paradisi, JHEP **1204** (2012) 060 [arXiv:1201.6204 [hep-ph]].
- [14] W. Altmannshofer, R. Primulando, C. -T. Yu and F. Yu, JHEP **1204** (2012) 049 [arXiv:1202.2866 [hep-ph]].
- [15] C. -H. Chen, C. -Q. Geng and W. Wang, Phys. Rev. D **85** (2012) 077702 [arXiv:1202.3300 [hep-ph]].
- [16] T. Feldmann, S. Nandi and A. Soni, JHEP **1206** (2012) 007 [arXiv:1202.3795 [hep-ph]].
- [17] O. Gedalia, J. F. Kamenik, Z. Ligeti and G. Perez, Phys. Lett. B **714** (2012) 55 [arXiv:1202.5038 [hep-ph]].
- [18] T. Mannel and N. Uraltsev, Phys. Rev. D **85** (2012) 096002 [arXiv:1202.6270 [hep-ph]].
- [19] H. -n. Li, C. -D. Lu and F. -S. Yu, Phys. Rev. D **86** (2012) 036012 [arXiv:1203.3120 [hep-ph]].
- [20] E. Franco, S. Mishima and L. Silvestrini, JHEP **1205** (2012) 140 [arXiv:1203.3131 [hep-ph]].

- [21] J. Brod, Y. Grossman, A. L. Kagan and J. Zupan, JHEP **1210** (2012) 161 [arXiv:1203.6659 [hep-ph]].
- [22] G. Hiller, Y. Hochberg and Y. Nir, Phys. Rev. D **85** (2012) 116008 [arXiv:1204.1046 [hep-ph]].
- [23] Y. Grossman, A. L. Kagan and J. Zupan, Phys. Rev. D **85** (2012) 114036 [arXiv:1204.3557 [hep-ph]].
- [24] T. Mannel and N. Uraltsev, JHEP **1303** (2013) 064 [arXiv:1205.0233 [hep-ph]].
- [25] H. -Y. Cheng and C. -W. Chiang, Phys. Rev. D **86** (2012) 014014 [arXiv:1205.0580 [hep-ph]].
- [26] G. Isidori and J. F. Kamenik, Phys. Rev. Lett. **109** (2012) 171801 [arXiv:1205.3164 [hep-ph]].
- [27] B. Keren-Zur, P. Lodone, M. Nardecchia, D. Pappadopulo, R. Rattazzi and L. Vecchi, Nucl. Phys. B **867** (2013) 429 [arXiv:1205.5803 [hep-ph]].
- [28] S. Bertolini, J. O. Eeg, A. Maiezza and F. Nesti, Phys. Rev. D **86** (2012) 095013 [arXiv:1206.0668 [hep-ph]].
- [29] R. Barbieri, D. Buttazzo, F. Sala and D. M. Straub, JHEP **1210** (2012) 040 [arXiv:1206.1327 [hep-ph]].
- [30] C. -H. Chen, C. -Q. Geng and W. Wang, Phys. Lett. B **718** (2013) 946 [arXiv:1206.5158 [hep-ph]].
- [31] A. D. Dolgov, S. I. Godunov, A. N. Rozanov and M. I. Vysotsky, JETP Lett. **96** (2012) 290 [arXiv:1206.6652 [hep-ph]].
- [32] C. Delaunay, J. F. Kamenik, G. Perez and L. Randall, JHEP **1301** (2013) 027 [arXiv:1207.0474 [hep-ph]].
- [33] B. Bhattacharya, M. Gronau and J. L. Rosner, arXiv:1207.0761 [hep-ph].
- [34] F. J. Botella, G. C. Branco and M. Nebot, JHEP **1212** (2012) 040 [arXiv:1207.4440 [hep-ph]].
- [35] L. Da Rold, C. Delaunay, C. Grojean and G. Perez, JHEP **1302** (2013) 149 [arXiv:1208.1499 [hep-ph]].
- [36] J. Lyon and R. Zwicky, arXiv:1210.6546 [hep-ph].
- [37] D. Atwood and A. Soni, PTEP **2013** (2013) 9, 0903B05 [arXiv:1211.1026 [hep-ph]].



- [38] Y. Grossman and D. J. Robinson, JHEP **1304** (2013) 067 [arXiv:1211.3361 [hep-ph]].
- [39] G. Hiller, M. Jung and S. Schacht, Phys. Rev. D **87** (2013) 014024 [arXiv:1211.3734 [hep-ph]].
- [40] F. Buccella, M. Lusignoli, A. Pugliese and P. Santorelli, arXiv:1305.7343 [hep-ph].
- [41] A. Dighe, D. Ghosh and B. P. Kodrani, arXiv:1306.3861 [hep-ph].
- [42] G. Hiller, M. Jung and S. Schacht, arXiv:1311.3883 [hep-ph].
- [43] Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75** (2007) 036008 [hep-ph/0609178].
- [44] M. Bobrowski, A. Lenz, J. Riedl and J. Rohrwild, JHEP **1003** (2010) 009 [arXiv:1002.4794 [hep-ph]].
- [45] A. Kronfeld, these proceedings.
- [46] G. Wilkinson, these proceedings.
- [47] M. Jung, these proceedings.
- [48] S. Schacht, these proceedings.
- [49] I. Bertram, these proceedings.
- [50] N. Neri, these proceedings.
- [51] S. Fajfer, these proceedings.
- [52] A. Schwartz, these proceedings.
- [53] M. Charles, these proceedings.
- [54] G. Hiller, these proceedings.
- [55] M. Gersabeck, Mod. Phys. Lett. A **27** (2012) 1230026 [arXiv:1207.2195 [hep-ex]].
- [56] R. Aaij *et al.* [LHCb Collaboration], Eur. Phys. J. C **73** (2013) 2373 [arXiv:1208.3355 [hep-ex]].
- [57] G. Inguglia, arXiv:1311.2754 [hep-ex].
- [58] [LHCb Collaboration], LHCb-CONF-2013-003 (2013).

- [59] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **723** (2013) 33 [arXiv:1303.2614 [hep-ex]].
- [60] Y. Amhis *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].  
online update: <http://www.slac.stanford.edu/xorg/hfag/>
- [61] The Complete Sagas of the Icelanders, 2313 pages, Leifur Eiriksson Publishing Ltd (10 Aug 1997), ISBN-10: 9979929308, ISBN-13: 978-9979929307.
- [62] J. Charles *et al.* [CKMfitter Group Collaboration], Eur. Phys. J. C **41**, 1 (2005) [hep-ph/0406184].
- [63] M. Ciuchini, G. D’Agostini, E. Franco, V. Lubicz, G. Martinelli, F. Parodi, P. Roudeau and A. Stocchi, JHEP **0107**, 013 (2001) [hep-ph/0012308].
- [64] M. K. Gaillard and B. W. Lee, Phys. Rev. Lett. **33** (1974) 108.
- [65] G. Altarelli and L. Maiani, Phys. Lett. B **52** (1974) 351.
- [66] L. F. Abbott, P. Sikivie and M. B. Wise, Phys. Rev. D **21** (1980) 768.
- [67] M. Golden and B. Grinstein, Phys. Lett. B **222** (1989) 501.
- [68] P. A. Boyle *et al.* [RBC and UKQCD Collaborations], Phys. Rev. Lett. **110** (2013) 152001 [arXiv:1212.1474 [hep-lat]].
- [69] M. Luscher, Commun. Math. Phys. **105** (1986) 153.
- [70] M. Luscher, Nucl. Phys. B **354** (1991) 531.
- [71] M. Luscher, Nucl. Phys. B **364** (1991) 237.
- [72] L. Lellouch and M. Luscher, Commun. Math. Phys. **219** (2001) 31 [hep-lat/0003023].
- [73] M. T. Hansen and S. R. Sharpe, Phys. Rev. D **86** (2012) 016007 [arXiv:1204.0826 [hep-lat]].
- [74] A. Lenz, arXiv:1205.1444 [hep-ph].
- [75] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. D **87** (2013) 112010 [arXiv:1304.2600 [hep-ex]].
- [76] G. Aad *et al.* [ATLAS Collaboration], JHEP **1212** (2012) 072 [arXiv:1208.0572 [hep-ex]].

- [77] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **109** (2012) 171802 [arXiv:1208.2967 [hep-ex]].
- [78] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **85** (2012) 032006 [arXiv:1109.3166 [hep-ex]].
- [79] A. Lenz and U. Nierste, arXiv:1102.4274 [hep-ph].
- [80] A. Lenz and U. Nierste, JHEP **0706** (2007) 072 [hep-ph/0612167].
- [81] M. Ciuchini, E. Franco, V. Lubicz, F. Mescia and C. Tarantino, JHEP **0308** (2003) 031 [hep-ph/0308029].
- [82] M. Beneke, G. Buchalla, A. Lenz and U. Nierste, Phys. Lett. B **576** (2003) 173 [hep-ph/0307344].
- [83] M. Beneke, G. Buchalla, C. Greub, A. Lenz and U. Nierste, Phys. Lett. B **459** (1999) 631 [hep-ph/9808385].
- [84] M. Beneke, G. Buchalla and I. Dunietz, Phys. Rev. D **54** (1996) 4419 [Erratum-ibid. D **83** (2011) 119902] [hep-ph/9605259].
- [85] A. Lenz and T. Rauh, Phys. Rev. D **88** (2013) 034004 [arXiv:1305.3588 [hep-ph]].
- [86] D. Becirevic, PoS HEP **2001** (2001) 098 [hep-ph/0110124].
- [87] A. Djouadi and A. Lenz, Phys. Lett. B **715** (2012) 310 [arXiv:1204.1252 [hep-ph]].
- [88] E. Kuflik, Y. Nir and T. Volansky, Phys. Rev. Lett. **110** (2013) 091801 [arXiv:1204.1975 [hep-ph]].
- [89] O. Eberhardt, G. Herbert, H. Lacker, A. Lenz, A. Menzel, U. Nierste and M. Wiebusch, Phys. Rev. Lett. **109** (2012) 241802 [arXiv:1209.1101 [hep-ph]].
- [90] M. J. Savage, Phys. Lett. B **257** (1991) 414.
- [91] L. -L. Chau and H. -Y. Cheng, Phys. Lett. B **280** (1992) 281.
- [92] L. Silvestrini, private communication.
- [93] RAaij *et al.* [LHCb Collaboration], Phys. Lett. B **726** (2013) 623 [arXiv:1308.3189 [hep-ex]].
- [94] RAaij *et al.* [LHCb Collaboration], arXiv:1310.7953 [hep-ex].
- [95] S. Harnew, arXiv:1311.4729 [hep-ex].

- [96] B. Bhattacharya, D. London, M. Gronau and J. L. Rosner, Phys. Rev. D **87** (2013) 074002 [arXiv:1301.5631 [hep-ph]].
- [97] R. Aaij *et al.* [LHCb Collaboration], arXiv:1310.7201 [hep-ex].